EFFECT OF EXTREME TEMPERATURE ON STEEL

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An Investigation Into the Effect of Extreme Temperatures on the Tensile Properties of Steels

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MAY 27, 1920

APPROVED: Geo. F. Gebhardt

Professor of Mechanical Engineering

H. M. R...

Dean of Engineering Studies

Dean of Cultural Studies

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PREFACE

With the advent of superheated steam in modern power practice and the use of high temperatures in internal combustion engines, both of the slow burning Diesel and the explosion types, reliable data on the tensile characteristics of the metals employed in these machines at these high temperatures has been found wanting. Due to this element of uncertainty that enters into the design of apparatus employed in this work, a factor of safety a great deal larger than necessary must be used or the wrong material may be employed resulting in destruction of the apparatus or undue expense, as the case may be.

This investigation was made with a view of arriving at some definite conclusions of this seemingly most important subject. Where materials are used subject to these conditions it is evident that they will not all stand up

the same. Having the data pertaining to the characteristics of a metal at these temperatures, it is a simple matter to choose the correct one to be employed. Three different steels were investigated: a low carbon, a medium carbon and a tool steel.

The authors wish to express their deepest gratitude to Professor P.C.Huntley without whose untiring interest and co-operation this investigation would have been impossible.

METHOD

An outline sketch of the general scheme employed is shown in Figure 1. An electric furnace (F) was used for heating the test bars. The current for this furnace was taken from the ordinary 110 volt line and the temperature controlled thru a carbon rheostat (R). A calibrated pyrometer (P), having its thermal junction as close to the probable point of rupture of the test bar as was possible, registered the temperature.

In order to reduce the source of error due to ascertaining the temperature of the bar at the point of rupture, the specimen was allowed to soak at the temperature it was to be pulled at for approximately five minutes before it was actually pulled. The heat radiates from the coil into the bar, and since the thermo-couple is between the two, manifestly the pyrometer will register a higher temperature at first

than what actually exists in the bar. This error may be very appreciable and in all investigations of this kind the correct reading of temperatures should receive first consideration. However, as mentioned previously, by allowing the bar to remain at that constant temperature for a sufficient length of time that will warrant the conclusion that the specimen has assumed the temperature of the surrounding medium, this source will be practically eliminated.

All tests were made on an Olson 60,000 pound testing machine located in the mechanical laboratory of the Armour Institute of Technology.

The bars were marked with two-inch punch marks in order to measure the elongation. As evident from the nature of the investigation, it would be impossible to use any instrument for measuring elongation such as an

extensometer. As soon as a bar was pulled and had reached such a temperature as made it possible to handle it, the elongation was measured. If the bars are permitted to cool to the ordinary room temperature from perhaps as high as 1400 or 1500 degrees Fahr., it is clear that the reading at the lower temperature will be less than one taken as soon as the pieces are removed from the holders of the machine. The amount of contraction in a two inch length may be small and whether the error involved will be appreciable or not will depend upon the accuracy with which measurements are made. The determination of elongation was made to the nearest one-one hundredth of an inch in two inches by the use of a screw caliper.

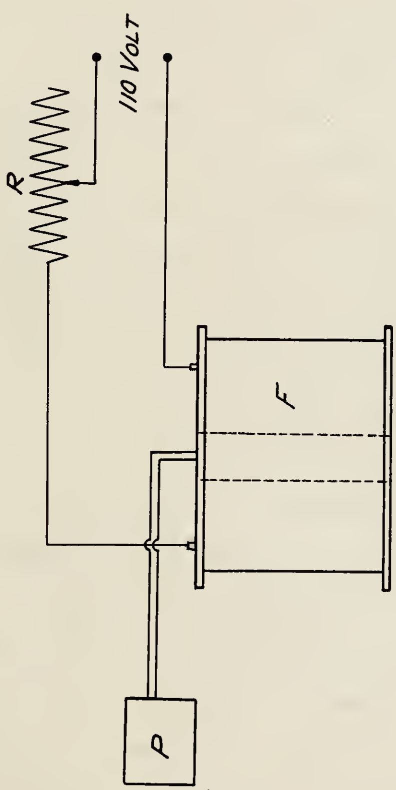


FIGURE 1

APPARATUS

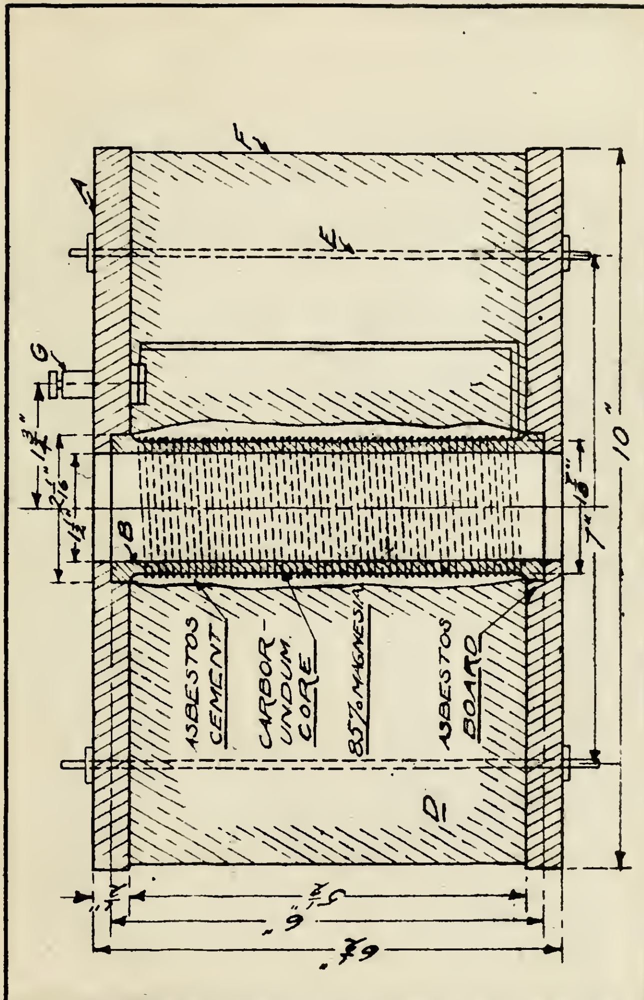
The selection of the type of furnace was of prime importance. It is shown in Figure 2 and its construction is as follows:

A cylinder (B) of dimensions shown, was wound with fifty-six turns of nickel-chrom resistance wire. It was found that by using a parallel winding the danger of over-heating and consequent burning out of the coil was avoided. Asbestos board being a refractory material, was found to be most satisfactory for the ends of the furnace. These boards were drilled in the center, the hole being large enough to admit the test specimen plus a clearance of about one-quarter of an inch. On one side of each board the hole was counter-bored in order to allow the tube carrying the heating coil to have a recess into which it could rest while the remainder of the parts were clamped together. An outside shell (F), of

galvanized iron served as a container for the insulting material (D), with which the intervening space was filled. The terminals for the heating coil were connected to binding posts (GG) as indicated. The entire contrivance was then clamped together with bolts (EE).

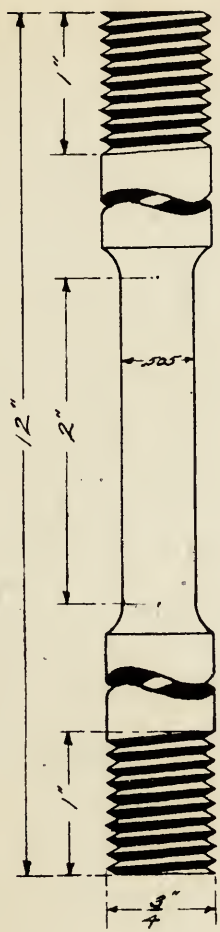
The tube around which the resistance wire was wound was of carborundum, altho any refractory material that could with-stand the high temperatures could have been used. In employing carborundum it was certain that there would be no danger of decomposition of the tube by heat.

The insulating material (D) was a fireproof, fibrous substance that is used quite extensively in heat insulation and consists chiefly of magnesium. This came in board form and in order to use it, it was broken up into a loose more or less homogeneous mass and then placed around the tube and packed but very little.


ASBESTOS CEMENT
CARBORUNDUM CORE
85% MAGNESIA
ASBESTOS BOARD
A
B
D
E
F
G
10"
6 3/4"
6"
5 1/2"
1 3/4"
1 1/2"
7"

The pyrometer employed was manufactured by the J.Hoskins Company and read to 3000 degrees Fahr. Calibrating the instrument against a standard thermo-couple (Bureau of Standards) and a pyrometer that was known to be accurate and a calibration curve plotted, it was a simple matter to read the corrected temperature direct from the curve. The ordinary method of calibration was employed, the standard couple consisting of platinum and platinum-iridium. This calibration curve is given in the appendix.

All test specimens were turned down by the authors in the Institute machine shops. The dimensions of the bars are shown in Figure 3. They were cut from stock material of three-quarter inch rod into lengths of twelve inches. They were then turned down in the center to a diameter of .510 inches for a length of two and one-half inches. By filing and polishing, the diameter was brought down to .505 inches, the



standard test specimen diameter. The ends were threaded for a length of one inch to receive a three-quarter inch nut. A diameter of .505 inches gives a crossectional area of very near one-fifth of a square inch. It is then a simple matter to convert the total load to pounds per square inch. The three-quarter inch nut is used in fastening the bars in the holder of the machine.

Plate 1 shows a photograph of the test specimen.

Plate 2 is the heating coil and tube.

Plate 3 shows the galvanized iron cylinder.

Plate 4 is the insulating material.

Plate 5 shows clearly how the apparatus was mounted on the testing machine.

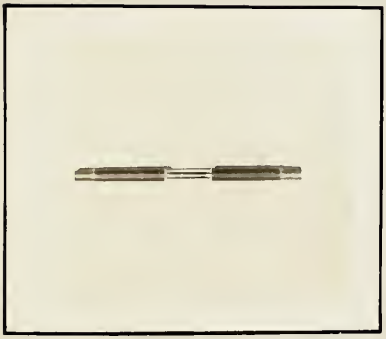


PLATE 1

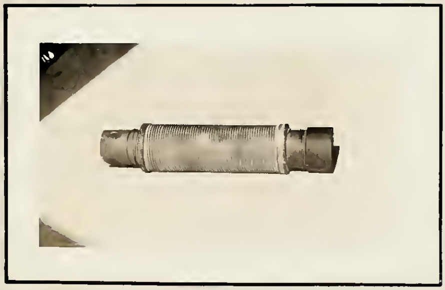


PLATE 2

PLATE 3

PLATE 4

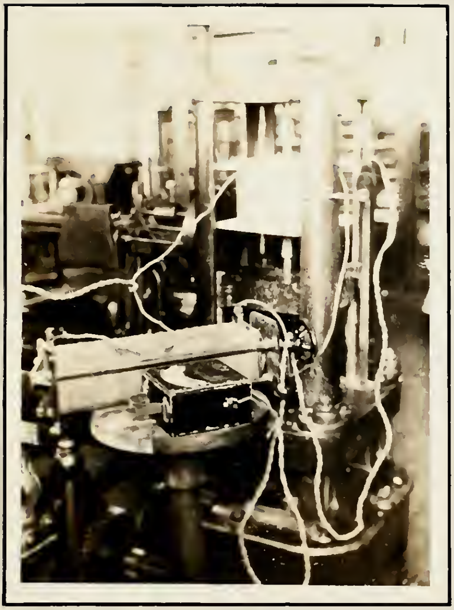


PLATE 5

PROCEDURE and DISCUSSION

Each specimen was numbered and a record kept of each one as shown in tables I, II and III. These tables show the actual data taken during the test and were later compiled into the form shown in tables IV, V and VI.

The temperature of the specimen was allowed to rise 50 degrees above that at which it was to be pulled. It was then permitted to cool down to the predetermined temperature and kept there for about five minutes, the higher the temperature the longer this time. In so doing, there was an almost absolute certainty that the specimen would be at the correct temperature as registered by the pyrometer. For instance, suppose that the bar was tp be pulled at 1000 degrees. If this was done at the instant that the pyrometer registered 1000 degrees there would be a considerable error involved, as has been previously explained. However, by allowing

the temperature to rise a slight amount above this and then cooled an equal amount, the registered temperature will be approximately correct, because the air filled annular space around the specimen will cool faster than the bar itself.

The authors therefor feel justified in saying that the error incurred in reading temperatures was a neglible quantity.

As the temperature incraased it was found that the location of the yield point became less and less pronounced. When pulling specimens cold, it is a very simple matter to determine this very accurately either with the use of an extensometer or by watching the scale poise. The yield point shows up very well by a sudden drop in the poise. However, as the temperature becomes higher, altho a drop in the poise will occur, it immediately picks up again, and unless the poise is kept in a per-

fectly horizontal position by moving the scale weight, this point will be missed.

After each bar had been pulled, its reduced diameter was measured with a micrometer. At first, attempt was made to use an ordinary micrometer having flat jaws, but the nature of the rupture was such that a close accurate measurement could not be made. A special attachment was then constructed, consisting of two pointed caps made to fit snugly over the ends of the jaws so that access could be made to any shallow portion of a rupture that could not be reached by the ordinary micrometer. Knowing the zero reading of the instrument, this was deducted from the actual reading, giving the true reduced diameter. From these readings the percentage reduction of area was calculated and tabulated as in tables IV, V and VI.

After testing the specimens at each one-hundred degrees, from room temperature to

1400 degrees, the more doubtful points were rechecked where possible, especially those near and above 1000 degrees Fahr. No two bars will pull at exactly the same load, so it was manifestly necessary to recheck as many points as possible. The points marked with a cross were assumed to be in error because of their deviation from the average value of points determined for that temperature. They were placed on the graph merely as a matter of general information and not of any particular value.

TABLE I
(Steel O)

Specimen No.	Dia.	Temp. in Deg. Fahr.	Load	Yield	Elong.	Red. Dia.
20	.505	900	16220	7500	.42	.36[illegible]
19	"	900	15980	7800	.42	.365
3	"	1000	14900	4200	.63	.311
28	.504	1100	14400	1900	.60	.307
24	"	1200	14300	1100	.58	.302
4	"	1300	8200	300	.71	.180
1	"	1400	3100	50	.89	.084
21	"	800	16750	8500	.40	.353
18	"	800	14600		.37	.342
10	.506	800	15560	8500	.44	.345
31	"	900	16600	7500	.43	.359
17	.507	1000	18100	7700	.49	.374
30	.505	400	13120	9170	.70	.308
23	"	600	13400	8800	.50	.322
22	"	500	13140	8380	.63	.310
15	.504	700	13300	8150	.52	.328
8	"	800	15900	8400	.46	.344
16	.505	1100	14750		.65	.292
5	"	900	15400	5850	.64	.325
9	"	1000	14700	5470	.66	.292
14	.506	900	16150	7970	.43	.352
26	.504	800	16000	8030	.39	.352
12	.505	1000	15580	6100	.57	.328
2	.504	1100	14360		.64	.295
11	"	1200	10300	250	.65	.236
13	"	1300	6000	4500	.80	.127
32	"	1400	3800	500	.88	.065

TABLE II
(Steel A)

Specimen No.	Dia.	Temp. in Deg. Fahr.	Load	Yield	Elong.	Red. Dia.
A6	.505	cold	14900	9250		.336
A2	"	400	14100	9050	.64	.335
A23	"	500	14150	9120	.55	.348
A9	"	600	14800	8700	.48	.354
A 5	.504	700	14700	8800	.45	.358
A26	.505	800	15200	8100	.39	.363
A14	"	900	16300	8600	.39	.372
A20	.504	1000	16350	7200	.55	.369
A29	.505	1000	16550	7250	.43	.381
A10	"	1100	15900		.60	.334
A4	"	1100	16670	6130	.44	.384
A13	.504	1200	13460	5800	.64	.282
A28	.505	1100	16800	6350	.50	.376
A 7	"	1200	14600	6000	.63	.287
A18	"	1300	13550	5450	.63	.262
A25	.504	1400	4200	2600	.85	.077

TABLE III
(Steel B)

Specimen No.	Dia.	Temp. in Deg. Fahr.	Load	Yield	Elong.	Red. Dia.
15	.505	700	25340	24350		.428
14	"	800	23500	22450	.32	.385
13	"	400		26350	.15	.455
10	"	400	25120	24460	.22	.427
11	"	800		24570	.18	.450
16	"	1200	24120	21100	.33	.385
12	"	1000	23120	22400	.33	.385
9	"	500	24800	24300	.19	.437
7	"	600	26300	25600	.15	.482
6	"	700	26000	24900	.11	.454
4	"	900	28100	27000	.09	.467
5	"	1100	29000	25700		.387
1	.506	1300	23500	22160	.31	.352
2	.505	1400	6500	5800	.34	.453
8	"	800	27100	24600	.18	.426
3	"	Cold	25540	23400	.17	.415

TABLE IV
(Steel O)

Specimen No.	Load Lbs./Sq.In.	Yield Lbs./Sq.In.	Percent Red. of Area.
20	81100	: 37500	47.4
19	79900	39000	50.6
3	74500	21000	62.1
28	72200	9500	63.0
24	71500	5500	64.2
4	41000	1500	87.3
1	15500	250	92.3
21	83750	42500	51.1
18	73000		54.1
10	77800	42500	53.3
31	83000	37500	49.4
17	90500	38500	45.1
30	65600	45800	62.7
23	67000	44000	59.3
22	65700	41900	62.3
15	66500	40750	57.7
8	79500	42000	53.5
16	73750		66.6
5	77000	29250	58.5
9	73500	27350	66.6
14	80750	39850	51.3
26	80000	40150	51.3
12	77900	30500	57.7
2	71800		65.8
11	51500	1250	78.1
13	30000	42500	93.7
32	19000	2500	98.4

TABLE V
(Steel A)

Specimen No.	Load Lbs./Sq In.	Yield Lbs./Sq. In.	Percent Red. of Area.
A6	74500	46250	55.8
A2	70500	45250	56.0
A23	70750	45600	52.5
A9	74400	43500	50.8
A5	73500	44000	49.7
A26	76000	40500	48.4
A14	81500	43000	45.8
A20	81750	36000	46.2
A29	82750	36250	43.0
A10	79500		46.0
A4	83350	30650	42.0
A13	67300	29000	43.0
A28	84000	31750	45.0
A7	73000	30000	63.0
A18	67750	27350	73.0
A25	21000	13000	97.7

TABLE VI
(Steel B)

Specimen No.	Load Lbs./Sq. In.	Yield Lbs./Sq. In.	Percent Red. of Area.
15	126700	121750	28.0
14	117500	112250	41.7
13		131750	18.8
10	125600	122300	28.4
11		122850	20.5
16	120600	105500	41.7
12	115600	112000	41.7
9	124000	121500	25.0
7	131500	128000	9.0
6	130000	124500	19.1
4	140500	135000	14.6
5	145000	128500	41.1
1	17500	110800	51.4
2	32500	29000	19.4
8	135500	123000	28.8
3	127700	117000	32.5

CHEMICAL ANALYSIS

Sample	Si	Mn	C (combined)	P	S
O	.05	.54	.28	.011	.039
A	.03	.49	.39	.014	.050
B	.25	.36	1.14	.022	.032

RESULTS

Referring to curve 0-1 on the low carbon steel, we see that there is a decrease in tensile strength from the cold state to about 350 degrees. From here on a sudden increase occurs due to an increased bondage of some kind that takes place in the structure of the material. At 900 degrees there seems to be a break-down of the material with a constant decrease in tensile strength as the temperature increases.

The variation in elongation is as may be expected, (curve 0-2). That is: a minimum value where the tensile strength is a maximum.

The elastic limit gradually falls off with a maximum drop from 800 degrees on. However, it is almost constant up to the point where maximum tensile strength occurs.

The curve on reduction of area is rather interesting. At 800 degrees, the point of maximum tensile strength, the reduction is a minimum. Of course, as the temperature increases from 800 degrees, the reduction increases because of the tendency of the metal to assume a semi-fluid state.

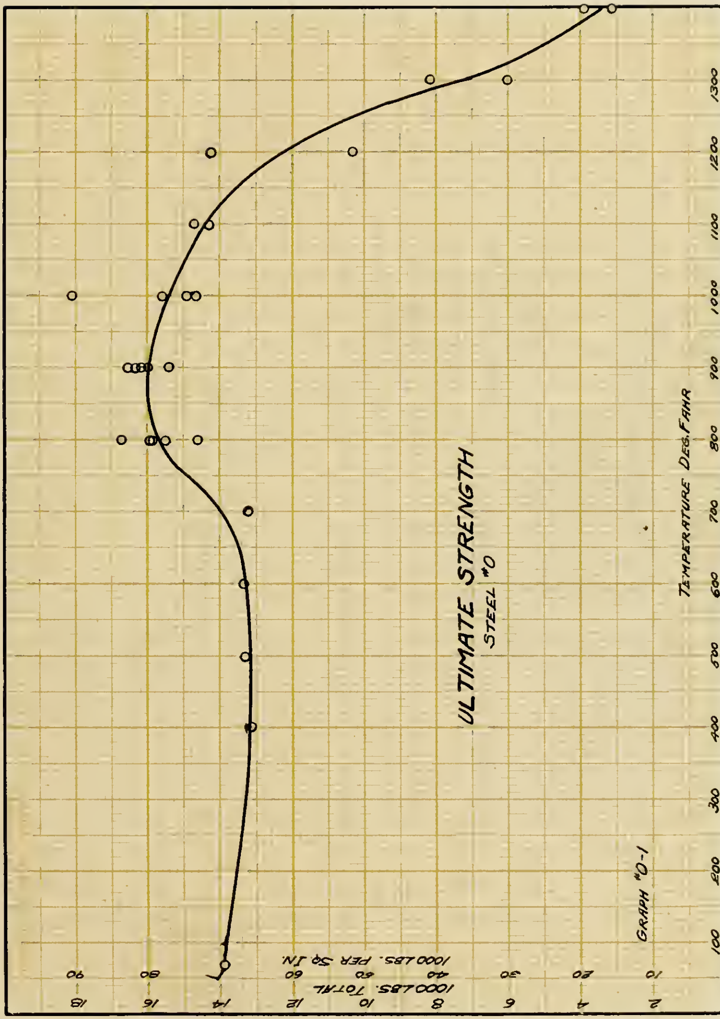
With the medium carbon steel similar curves are obtained, but the point of maximum tensile strength has increased to 1100 degrees approximately.

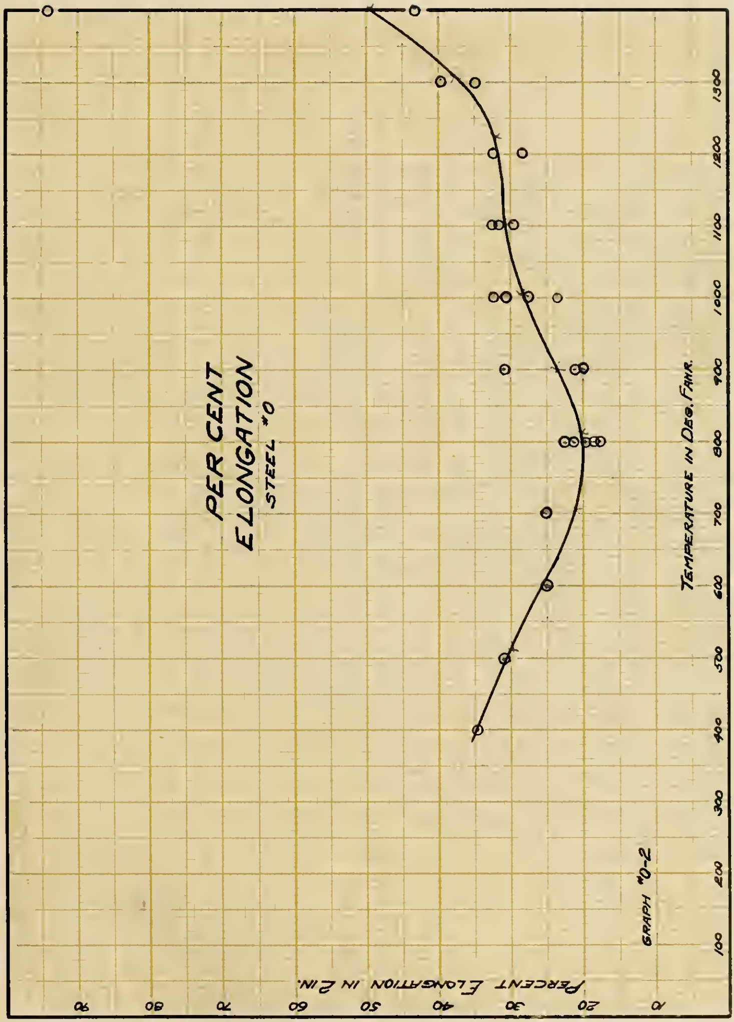
The curves on the tool steel are also similar, with a maximum tensile strength at 1100 degrees Fahr.

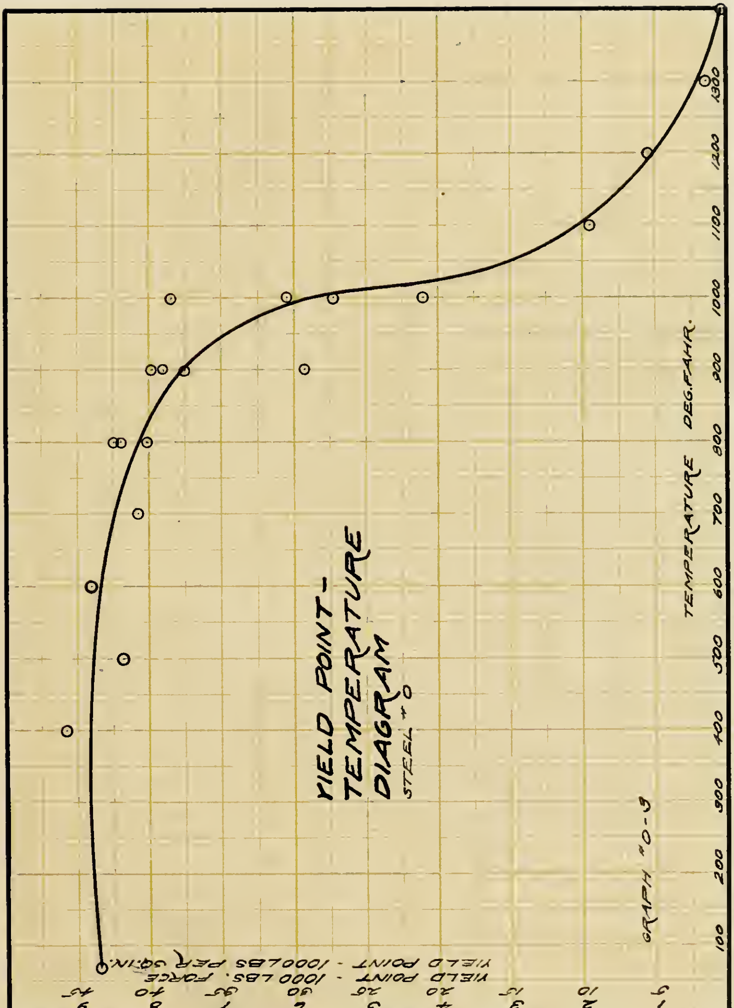
Plates 6 and 7 show the variation in the appearance of the fracture as the temperature increases. Plate 6 from cold to 700 degrees inclusive and Plate 7 from 800 to 1400 degrees inclusive. In the latter the sudden increase in reduction is clearly shown.

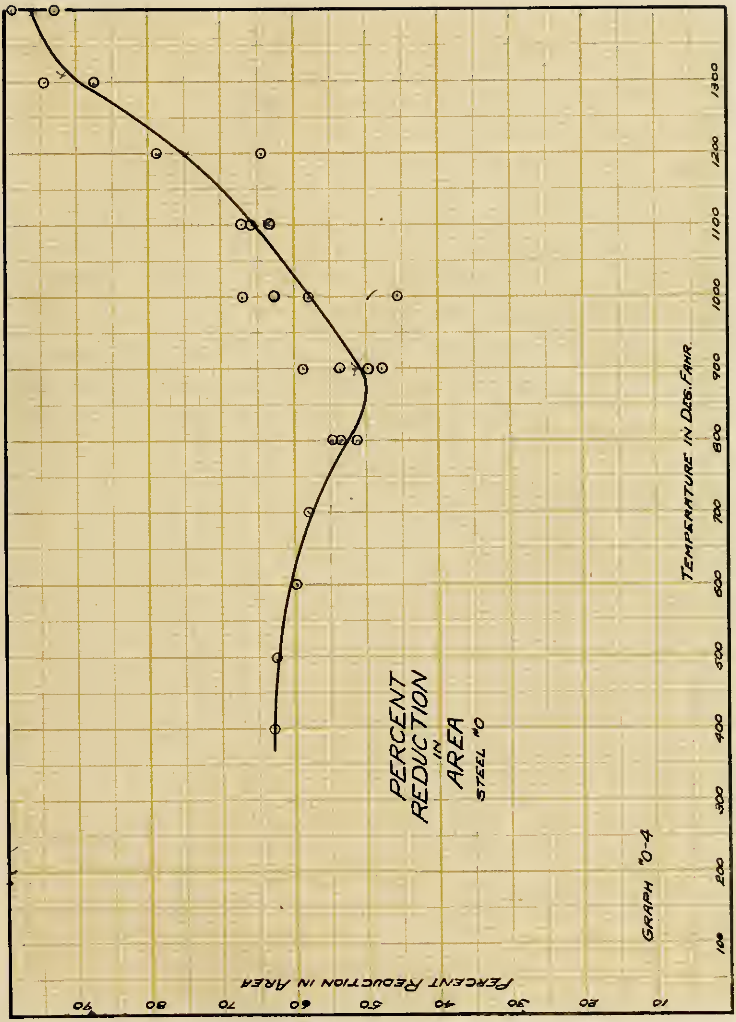
PLATE 6

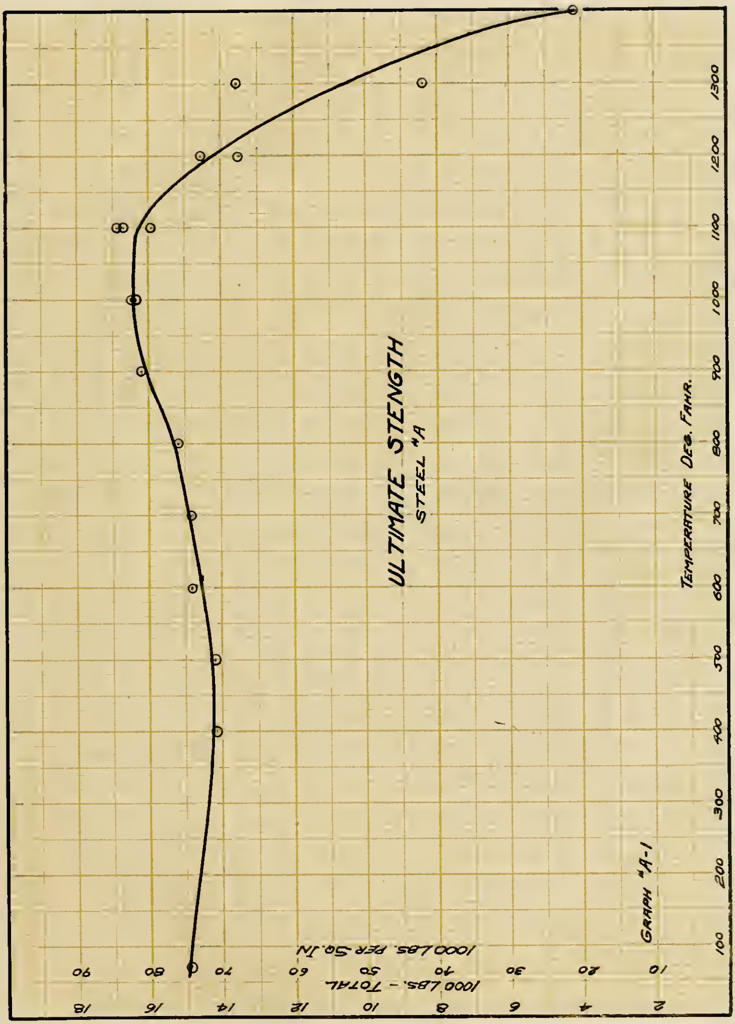
PLATE 7

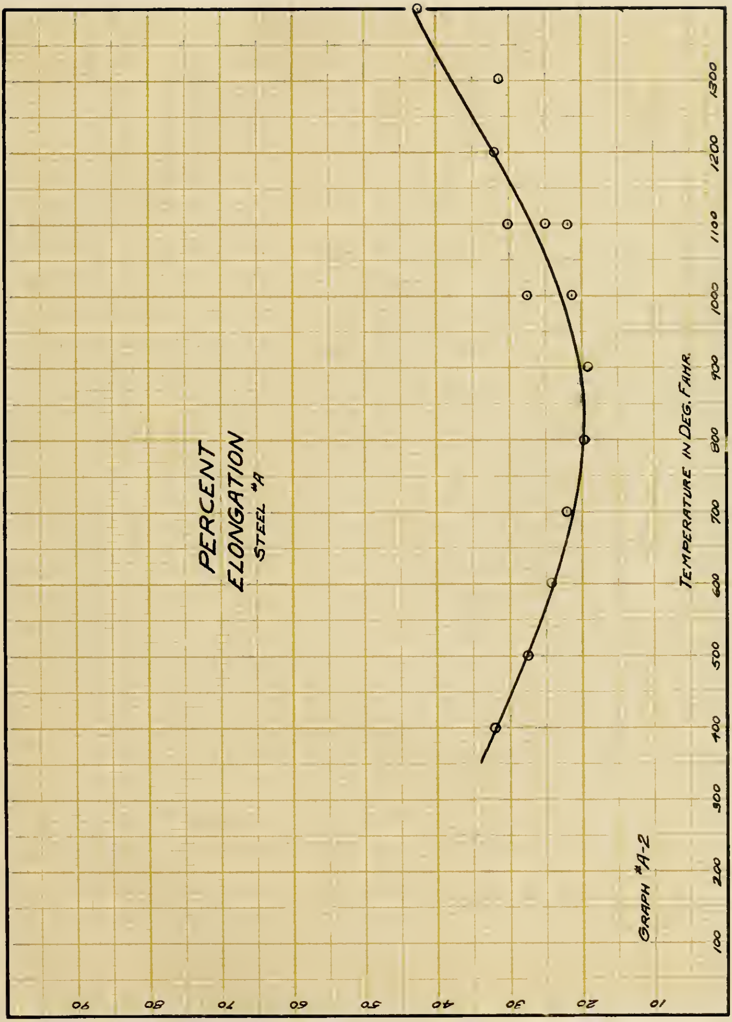

ULTIMATE STRENGTH
STEEL #O
TEMPERATURE DEG. FAHR
GRAPH #O-1
1000 LBS. TOTAL
1000 LBS. PER SQ. IN.
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
2
4
6
8
10
12
14
16
18
10
20
30
40
50
60
70
80
90

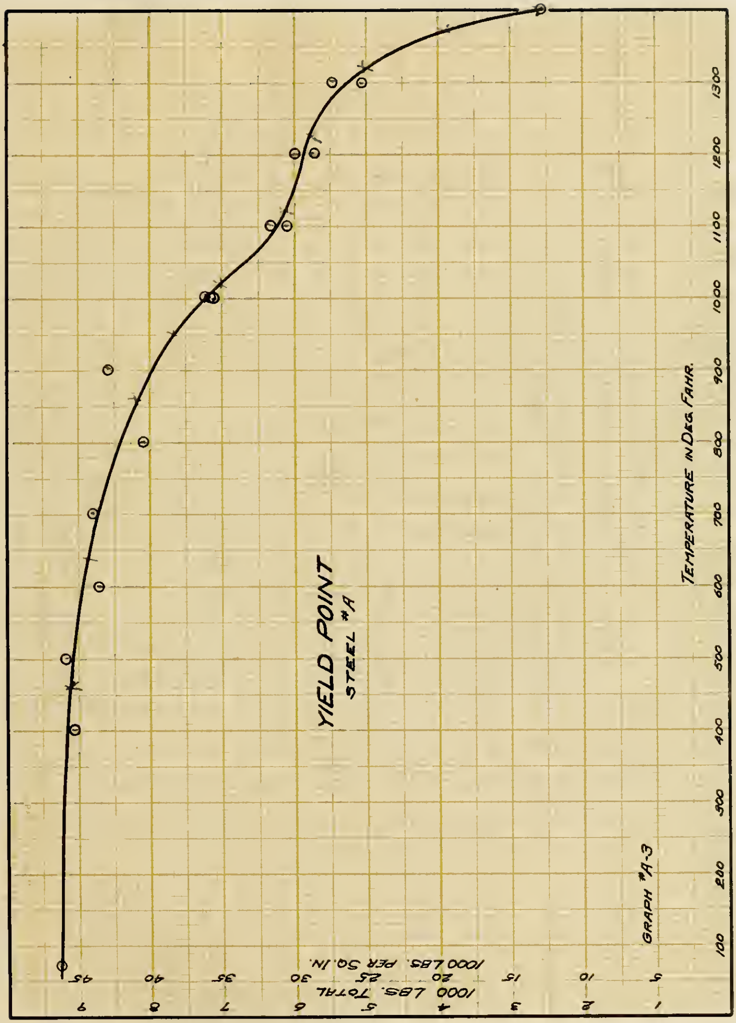

PER CENT
ELONGATION
STEEL #0
TEMPERATURE IN DEG. FAHR.
PERCENT ELONGATION IN 2 IN.
GRAPH #0-2
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
10
20
30
40
50
60
70
80
90

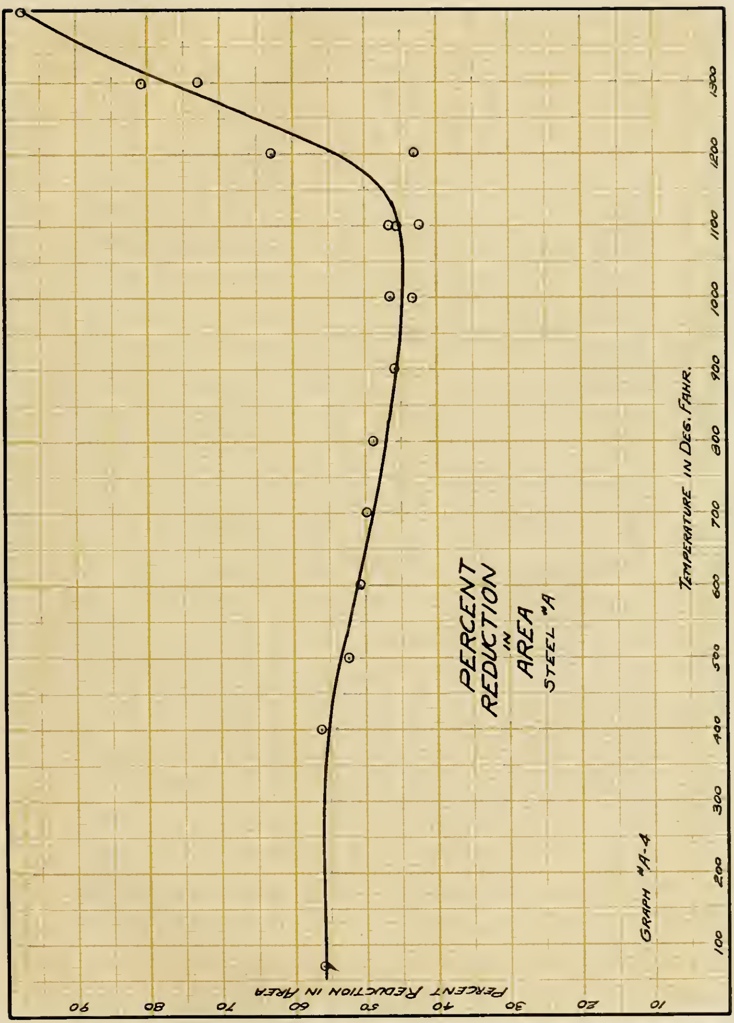

YIELD POINT -
TEMPERATURE
DIAGRAM
STEEL #O
TEMPERATURE DEG. FAHR.
GRAPH #O-3
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300

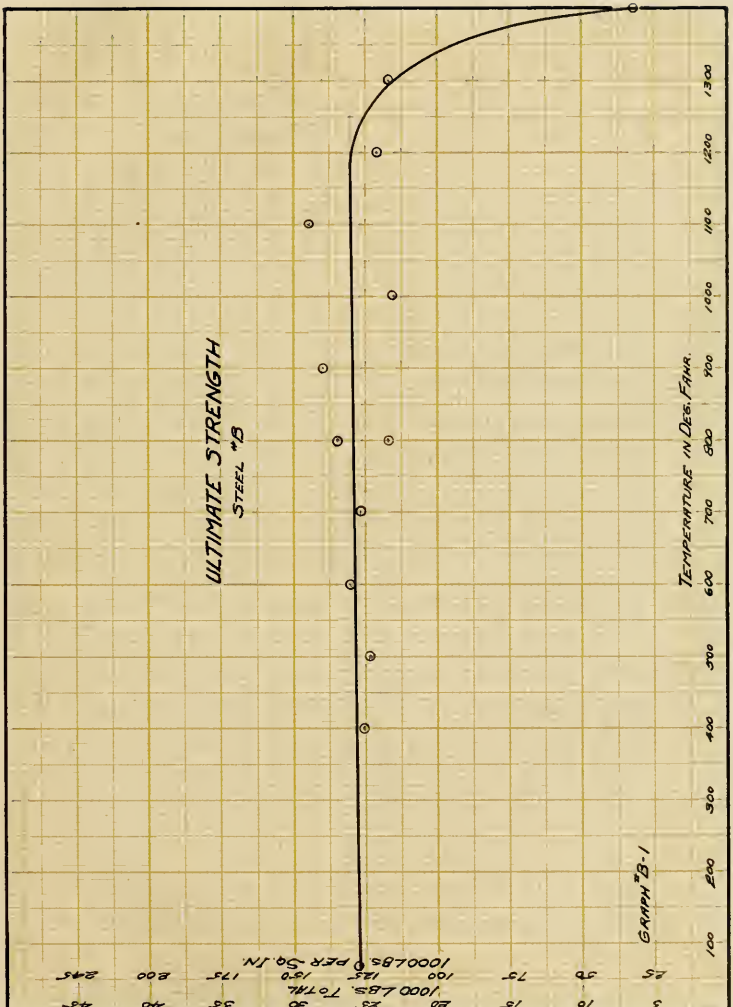

PERCENT REDUCTION IN AREA
STEEL #0
GRAPH #0-4
TEMPERATURE IN DEG. FAHR.
PERCENT REDUCTION IN AREA

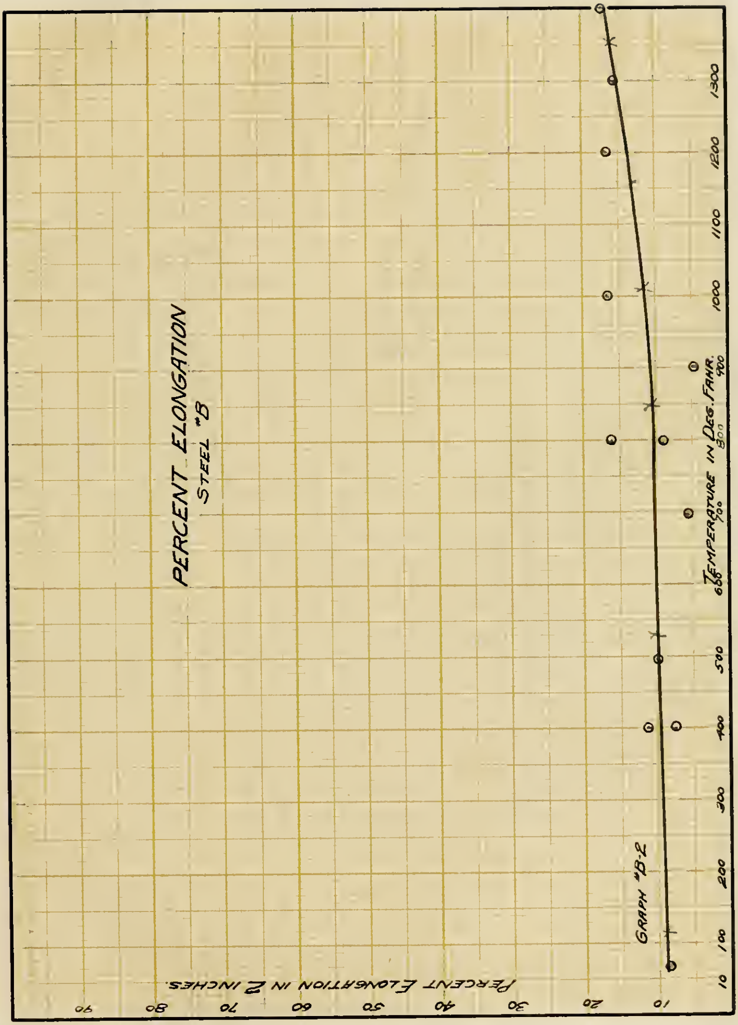

ULTIMATE STENGTH
STEEL #A
TEMPERATURE DEG. FAHR.
GRAPH #A-1
1000 LBS. PER SQ. IN
1000 LBS. - TOTAL
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300
10 20 30 40 50 60 70 80 90
2 4 6 8 10 12 14 16 18

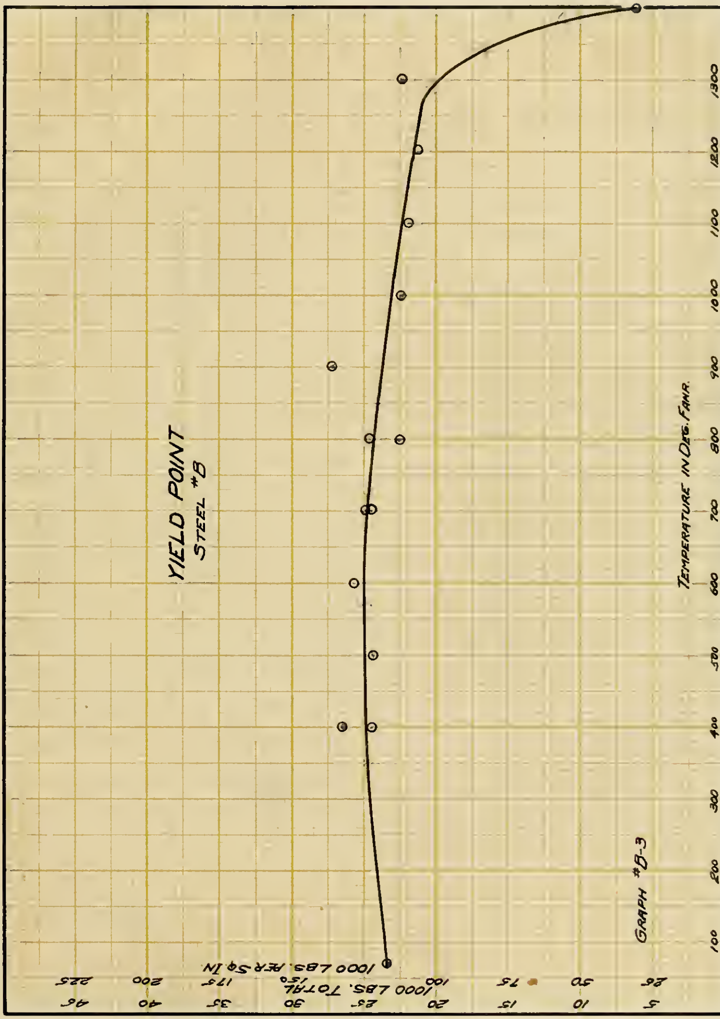

PERCENT
ELONGATION
STEEL #A
TEMPERATURE IN DEG. FAHR.
GRAPH #A-2
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
10
20
30
40
50
60
70
80
90


YIELD POINT
STEEL #A
TEMPERATURE IN DEG. FAHR.
GRAPH #A-3
1000 LBS. PER SQ. IN.
1000 LBS. TOTAL
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
5
10
15
20
25
30
35
40
45
1
2
3
4
5
6
7
8
9


PERCENT
REDUCTION
IN
AREA
STEEL #A
GRAPH #A-4
TEMPERATURE IN DEG. FAHR.
PERCENT REDUCTION IN AREA
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300
10 20 30 40 50 60 70 80 90


ULTIMATE STRENGTH
STEEL #B
TEMPERATURE IN DEG. FAHR.
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300
GRAPH #B-1
1000 LBS. PER SQ. IN.
25 50 75 100 125 150 175 200 225
1000 LBS. TOTAL
5 10 15 20 25 30 35 40 45


PERCENT ELONGATION
STEEL "B
GRAPH "B-2
TEMPERATURE IN DEG. FAHR.
10
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
PERCENT ELONGATION IN 2 INCHES.
10
20
30
40
50
60
70
80
90



YIELD POINT
STEEL #B
TEMPERATURE IN DEG. FAHR.
GRAPH #B-3
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1000 LBS. TOTAL
1000 LBS. PER SQ. IN


PERCENT REDUCTION IN AREA
TEMPERATURE DEG. FAHR.
GRAPH #B-4
PERCENT REDUCTION IN AREA
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300
10 20 30 40 50 60 70 80 90

In order to understand and investigate in detail the results of these tests and similar ones, photo-micrographs of the specimens should be taken and an individual study made of each so as to form a sound basis upon which conclusions may be drawn. The extent to which such an investigation can and should be carried is very great, but time did not permit the authors to make more than a mere start, as it were. It is hoped that the brief material furnished herewith will arouse others to carry the work on and go into it in more detail.

BIBLIOGRAPHY

A short resume of some of the work already done along these lines is given below. What little investigation that has been done has dealt with temperatures not any higher than 500 or 600 degrees, as a rule. Those mentioned below have gone to 1000 degrees Fahr. or more.

1. The manufacturers of the "Vulcan Soot Cleaner" have gone into the matter to a certain extent, because of the fact that soot cleaners are often placed where temperatures are comparatively high.

They found that with wrought iron the ultimate strength drops very rapidly when in the neighborhood of 1000 degrees Fahr. At this temperature the elastic limit drops off very abruptly. In other words, elements made of this metal alone are liable to sag at this temperature due to their own weight and be-

come distorted in a short time.

(Power Plant Engineering-Vol.22
August 1918)

2. The Crane Company of Chicago have done considerable work along this line for use in the manufacture of their valves and fittings for high temperature, high pressure steam.

A maximum tensile strength occurred in the neighborhood of 500 degrees using cold rolled steel.

3. Prof. Martens presented a paper to the Institute of Civil Engineers (England) in 1891, the paper being published in Vol. 104 of the Proceedings. However, he dealt with iron and found that maximum strength occurred at 200 to 300 degrees.

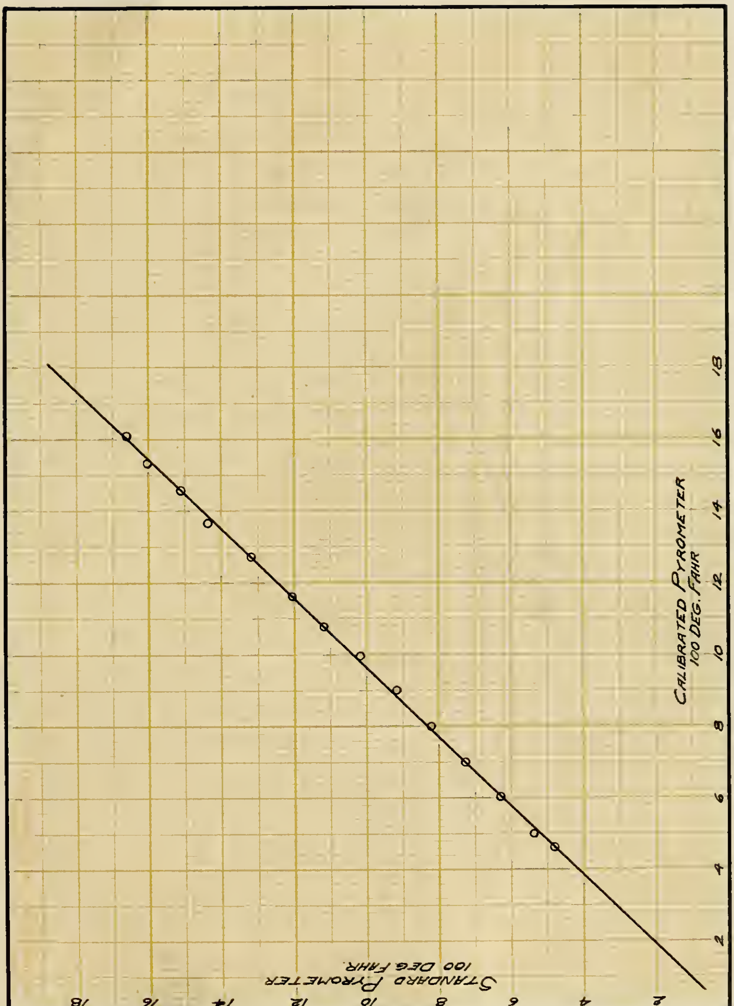
4. E.H.Schulz, Military Engineer, describes in "Zeitschrift des Vereines Deutscher Ingenieure" for January 1915, an investigation made by him upon several alloy steels and among

those he finds that a plain carbon steel of about 50 point has a maximum tensile strength at 550 degrees Centigrade.(about 1020 deg. Fahr.)

5. Mr. H.S.Rawdon and MR. H.Scott of the Bureau of Standards have investigated the microstructure of iron and mild steel at temperatures as high as 950 degrees Centigrade. They have found that an appreciable change in composition and structure of the surface metal occurs in steel upon heating.

(Bureau of Standards,Sc. Paper, No. 356)

APPENDIX


Calibrated Pyrometer
100 Deg. Fahr
Standard Pyrometer
100 Deg Fahr.